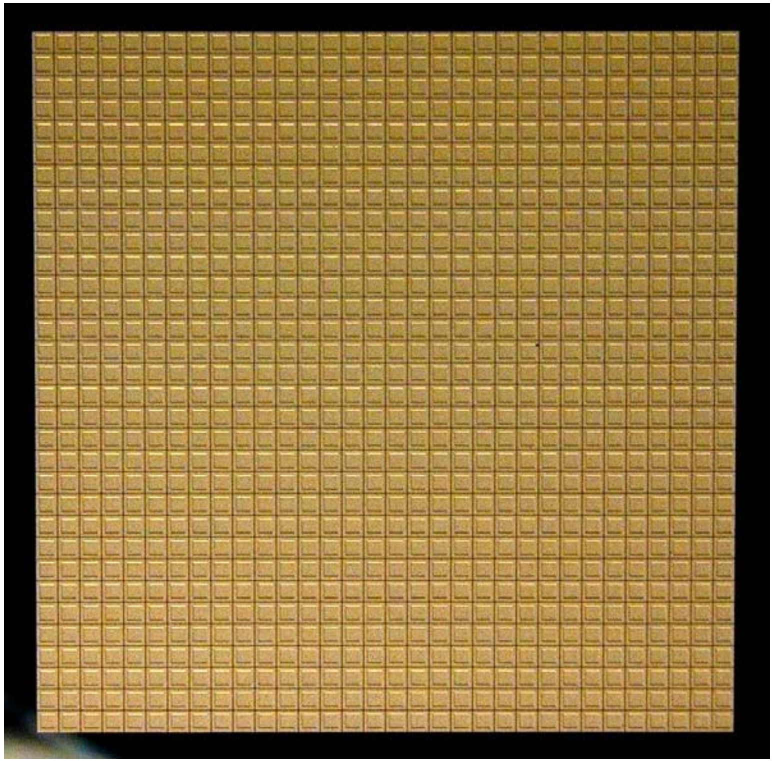
# X-Ray Microcalorimeters



**FST Meeting**
**Smithsonian Astrophysical Observatory**
**September 18, 2002**

# Agenda

Introduction and Overview 5 min

*Richard Kelley (GSFC)*

Progress on NTD Microcalorimeters 20 min

*Eric Silver (SAO)*

Progress on TES Microcalorimeters 40 min

*Enectali Figueroa (GSFC) & Steve Deiker (NIST)*

Progress on Magnetic Calorimeters 10 min

*Christian Enss (Brown University)*

# Astro-E2/XRS Microcalorimeter Array

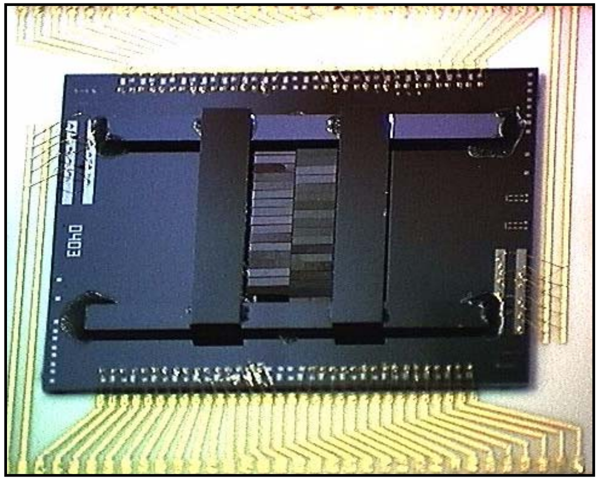
<u>Baseline array for Astro-E2/XRS</u>:

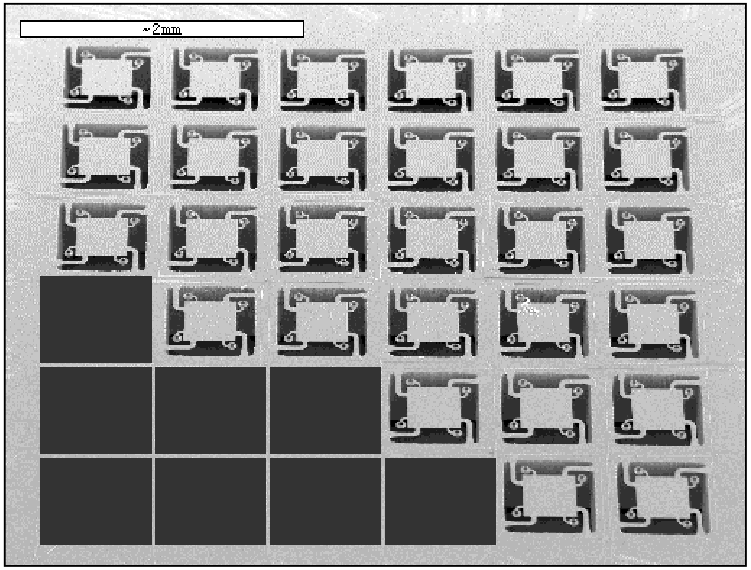
2 x 16 “bilinear” array
Rectangular pixels
12 eV resolution

Have two bilinear arrays that have successfully passed acceptance testing.

*Possibility* of square array with higher spectral resolution.

New design also offers many other benefits.



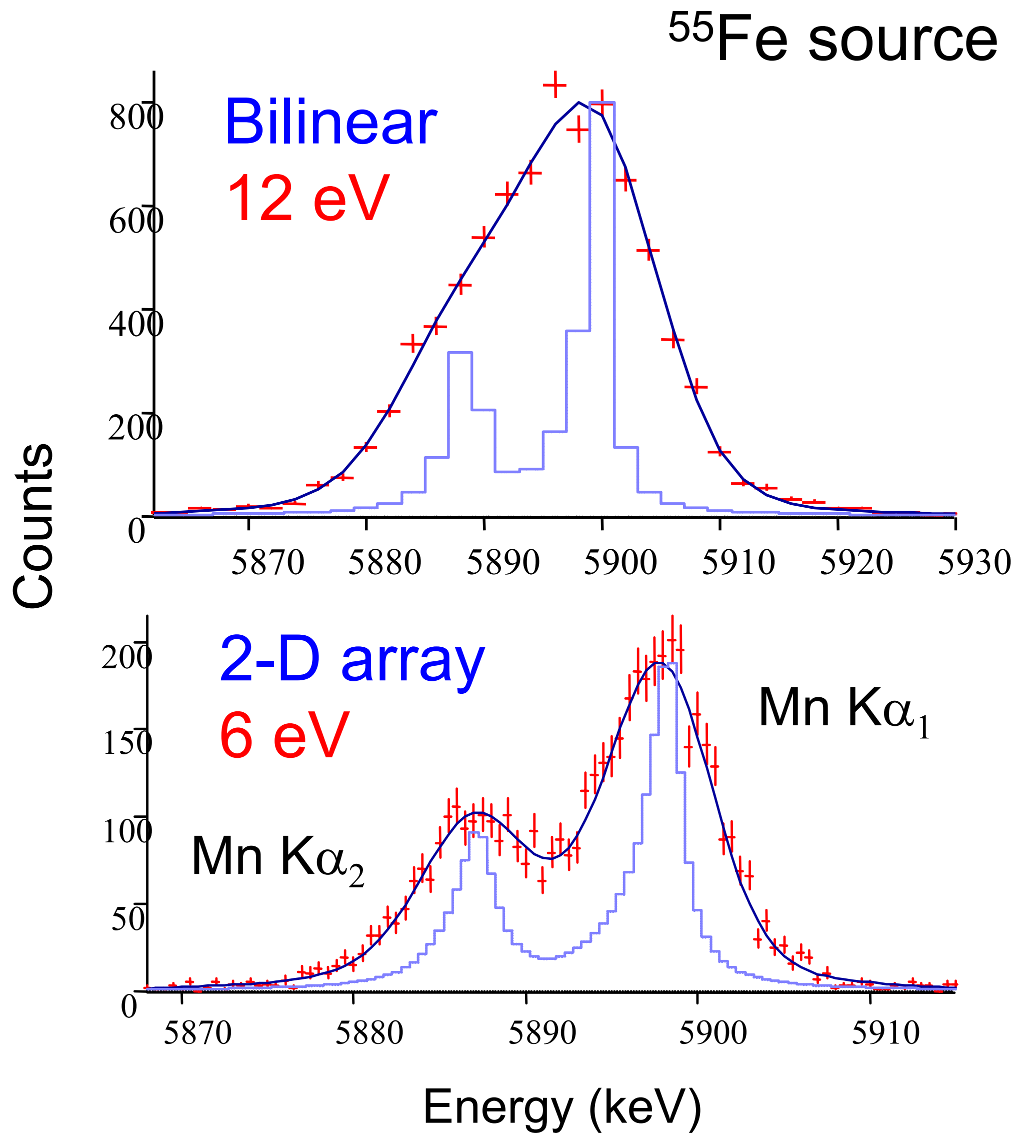


# Significantly Improved Energy Resolution

Energy resolution is close to theoretical limit of ideal detector and about a factor of 2 times better than bilinear array.

Factor of 2 improvement allows Fe-K lines, a key diagnostic for Astro-E2, to be almost fully resolved.

Extends diagnostic capabilities to lighter elements, and improves sensitivity to trace elements and velocity measurements.



# Summary of Benefits of Adopting 2-D Array

- Elimination of 1/f noise gives x 2 higher spectral resolution
- Faster pulse response gives x 2 higher margin against pulse-pileup
- Improved resolution uniformity for easier calibration and data analysis
- Improved mechanical margins against crack initiation in Si
- Fully-covered pixels effectively extends spectral band to lower energies
- *Two order of magnitude* improvement in detector heat sinking
- Improved in-flight calibration system increases instrument sensitivity
- Better match to x-ray optics for increased photon detection efficiency

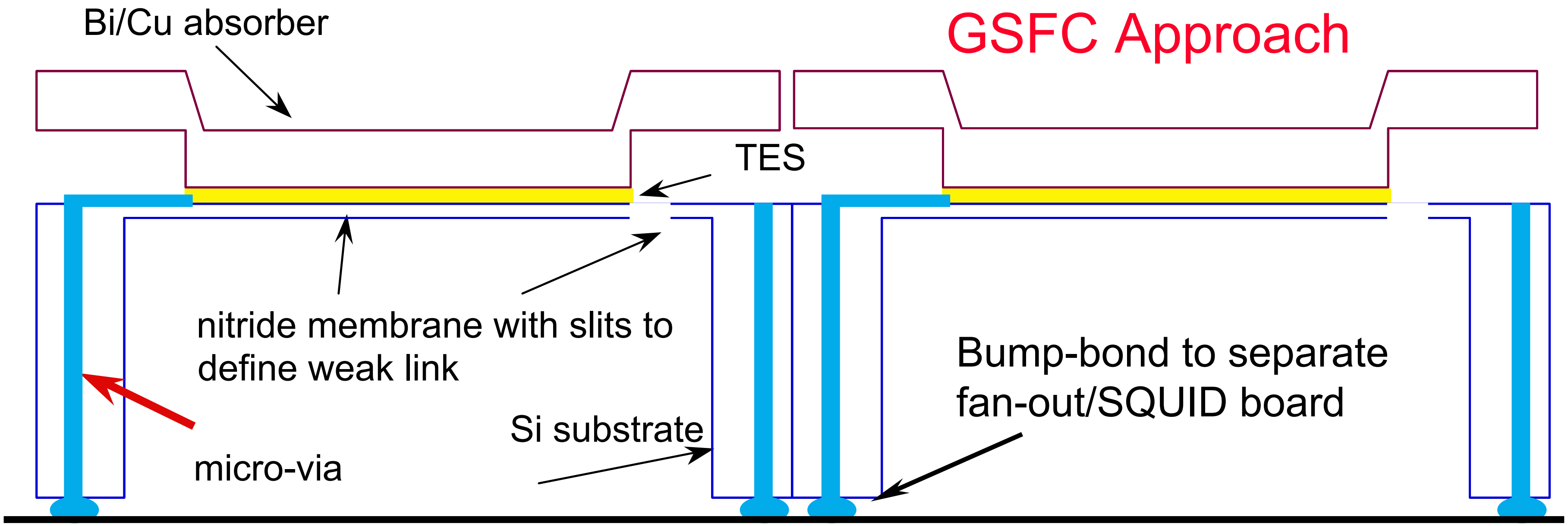
Working with NASA HQ to facilitate implementation

# Detector Requirements

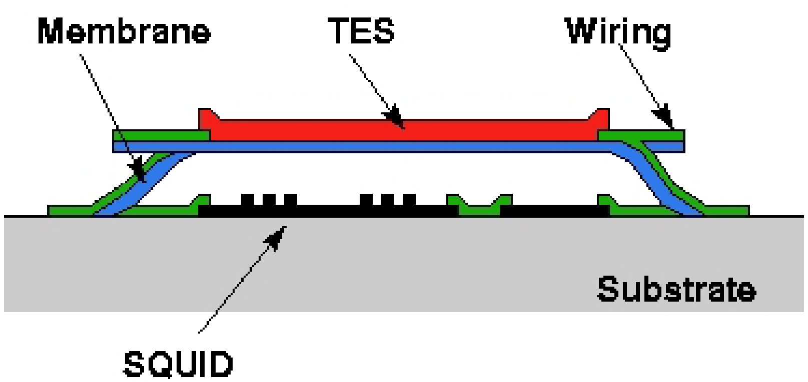
| Top-Level Requirement | | Derived Requirement |
|---|---|---|
| Energy Resolution | R=3000 from 6 to 8.5 keV (2 eV at 6 keV) | same |
| Pixel Size | 1/3 of HPD | 15" HPD $\Rightarrow$ 5"<br>$\therefore$ 250 $\mu$m |
| Field of View | 2.5 arcmin | 30 $\times$ 30 array |
| Detection Efficiency | Provide top level $A_{eff}$ | TBD, but approximately:<br>QE > 90% at 6 keV<br>array fill factor > 90% |
| Counting Rate | "handle" up to 1000 cps/pixel | $\tau_{eff}$ = 100 - 300 $\mu$sec |

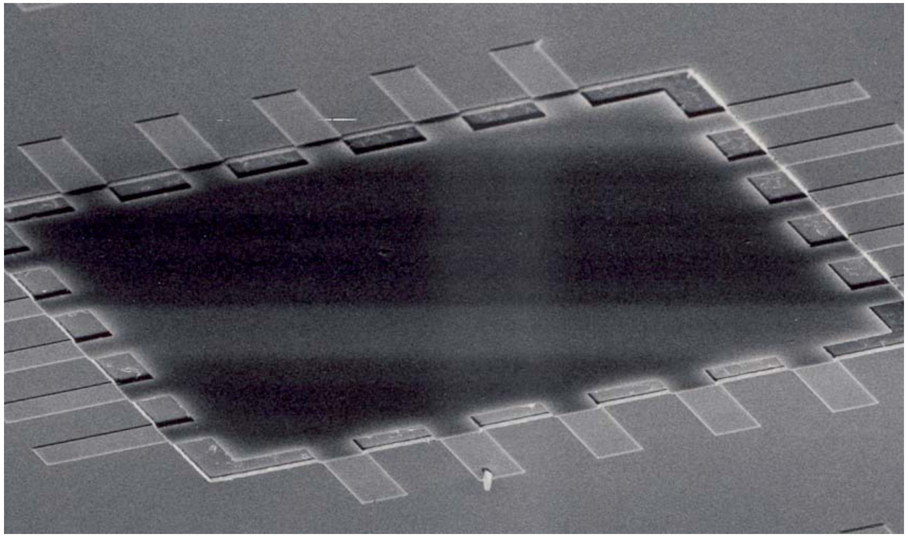
# TES Array Concepts

## GSFC Approach

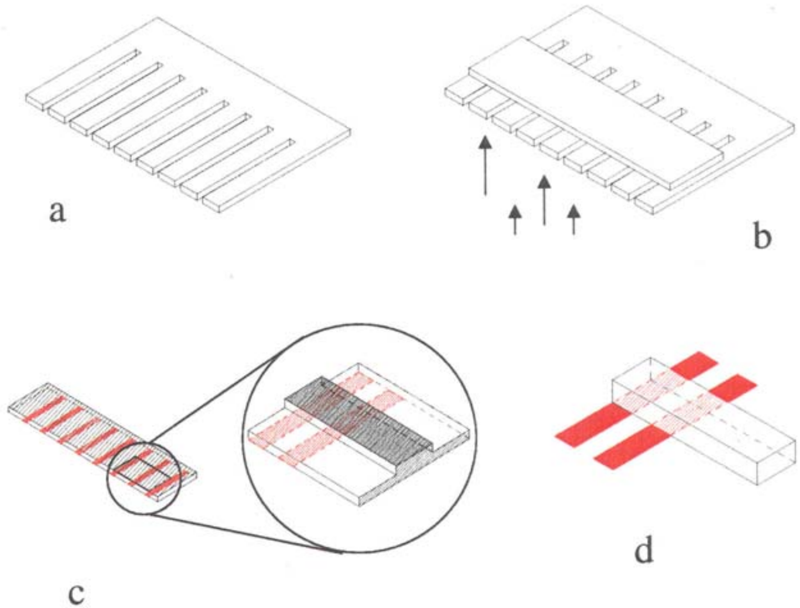


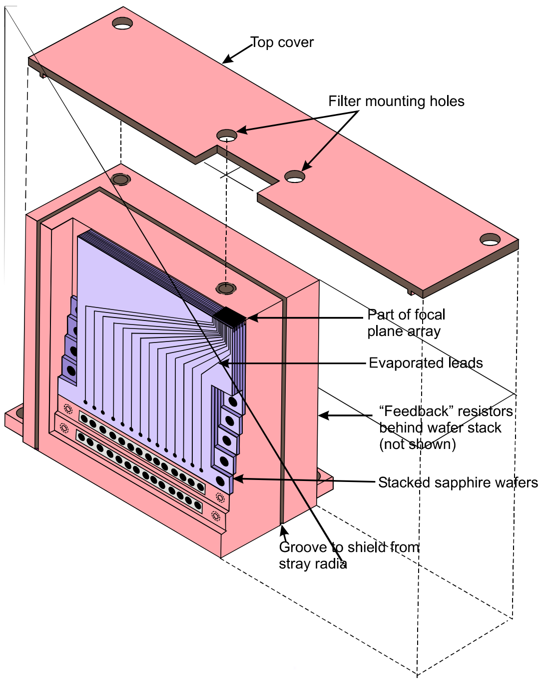

## NIST Idea:



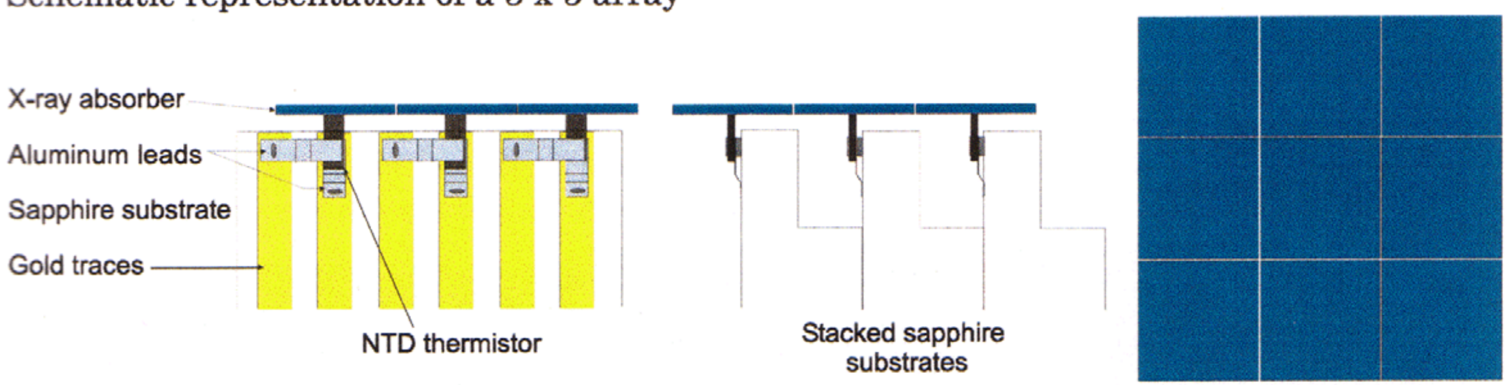



# NTD Ge Microcalorimeter Array



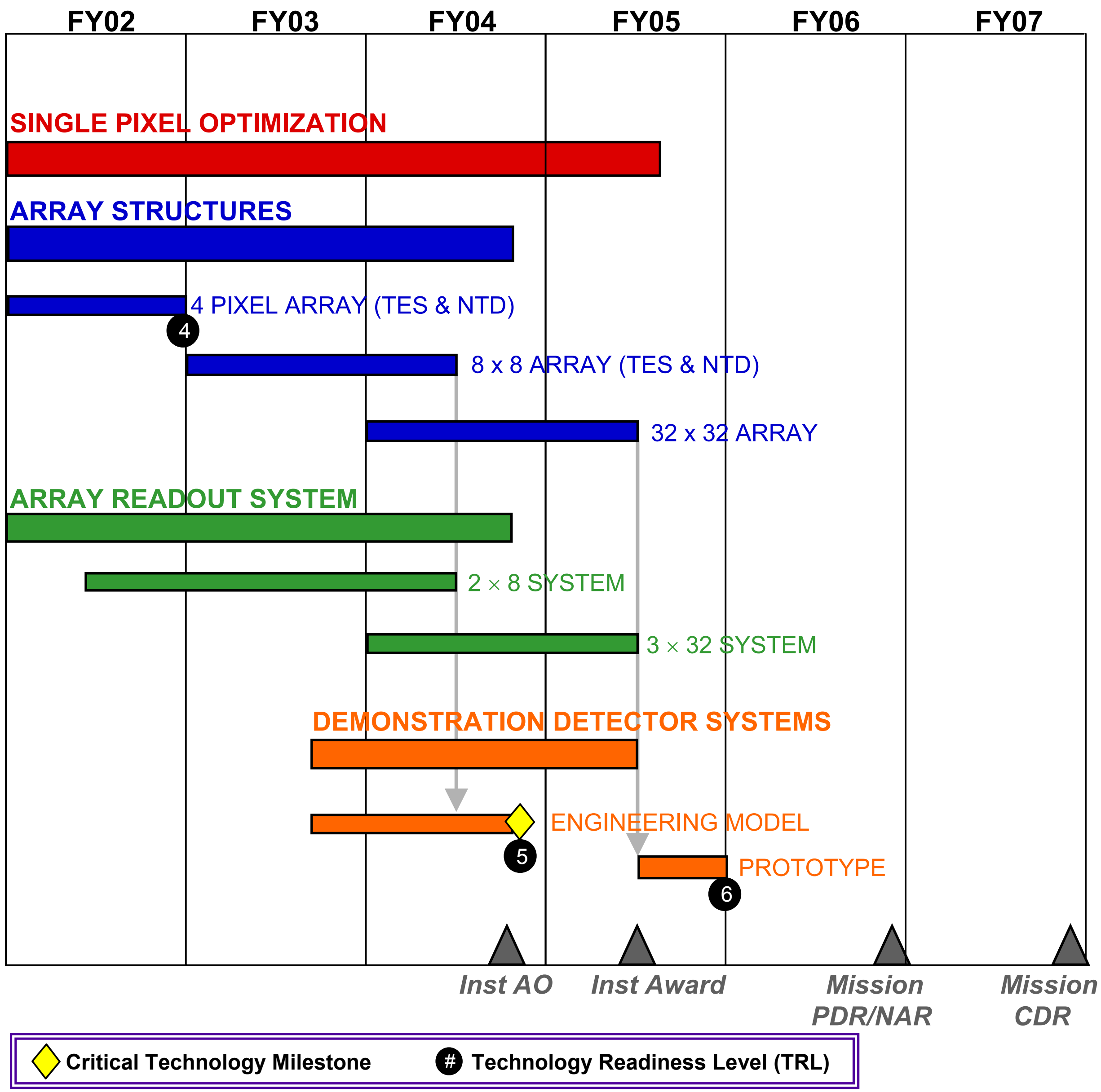

Schematic representation of a 3 x 3 array




Front View Side View Top View

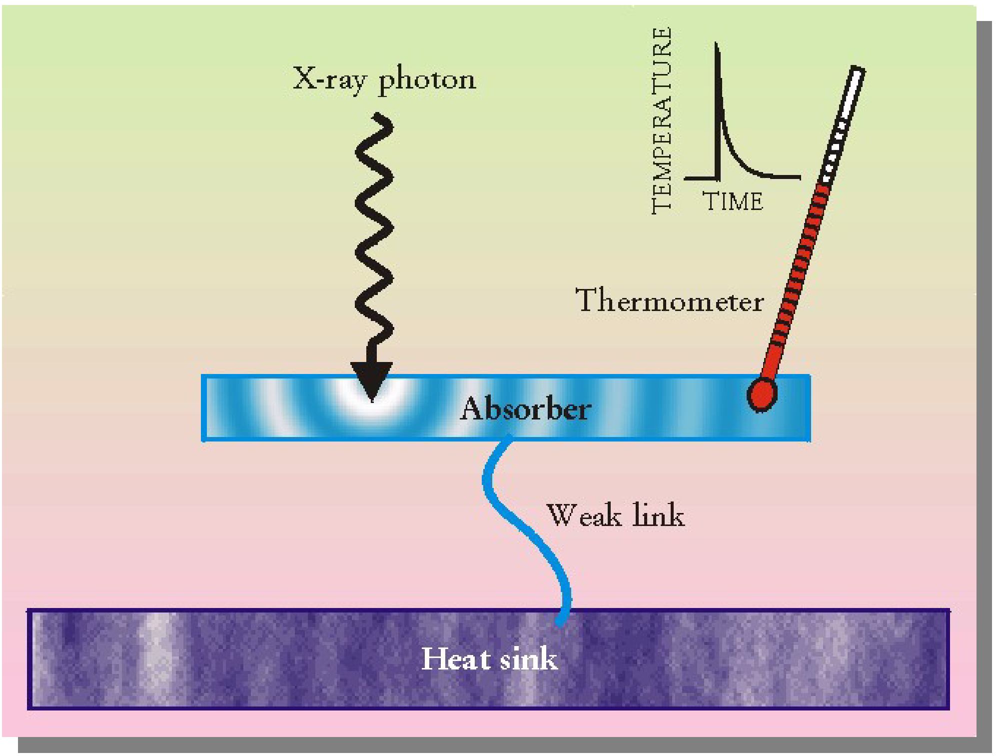
SAO

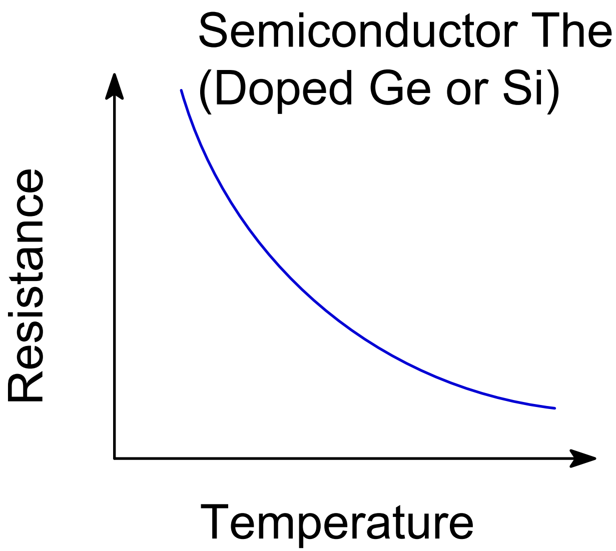
# Calorimeter Technology Roadmap

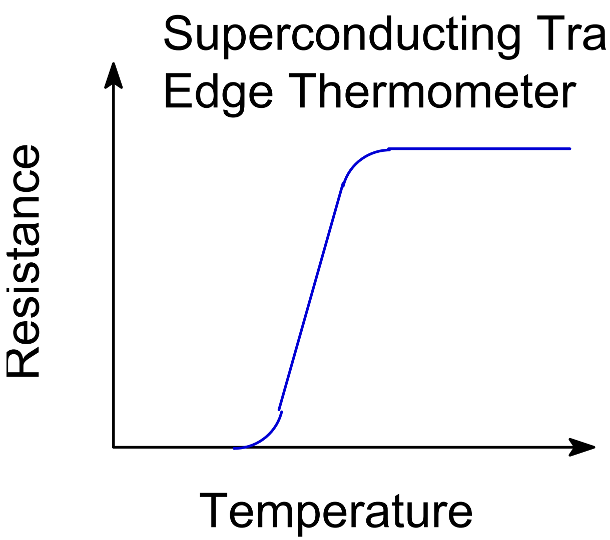


# Supplemental Material

# X-ray Microcalorimeter



# Overall Status

| Thermometer Types: | Energy Resolution |
| --- | --- |
| Al/Ag, Mo/Au, Mo/Cu TES | 2.0 - 2.5 eV at 1.5 keV |
| NTD Ge semiconductor | 4 - 6 eV at 6 keV |

Array Size

Only single pixel *test results* thus far (but small arrays have been fabricated)

Counting rate

Pulse decay time constants of ~ 300 μsec

Readout Schemes

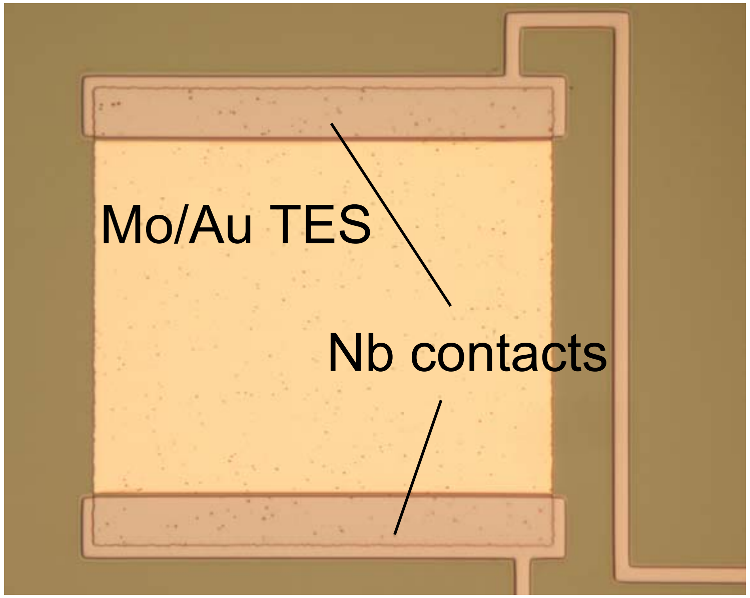
32 channel XRS system, analytical designs for larger JFET systems; MUX designs and functional systems for IR TES.

For TRL-6, we need to demonstrate

- 2-4 eV at 6 keV (and below) with high degree of pixel-pixel uniformity
- Robust array scheme with high-yield process.
- Faster pulses (< 300 μsec)
- Large array readout schemes compatible with extended life mission.

# Recent Progress and Issues

## GSFC:




Electrical contact to TES.

Poor step coverage with sputtered Nb leads.

Have several recovery approaches;

Aluminum leads are working, but we need to pursue a robust solution.

Undercutting of bilayer

Produced TES protection mask to protect Mo during certain etch steps.

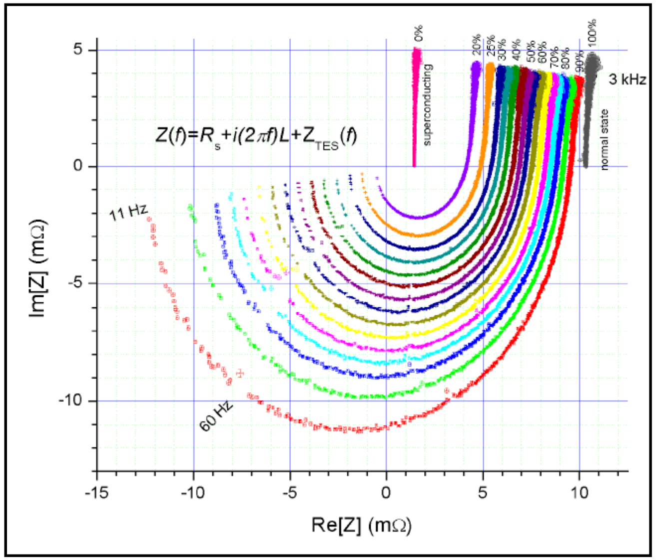
Pin hole defects in Au layer of bilayer

Solved problem with tungsten crucible w/Ta pellets.

Bilayer thickness optimization

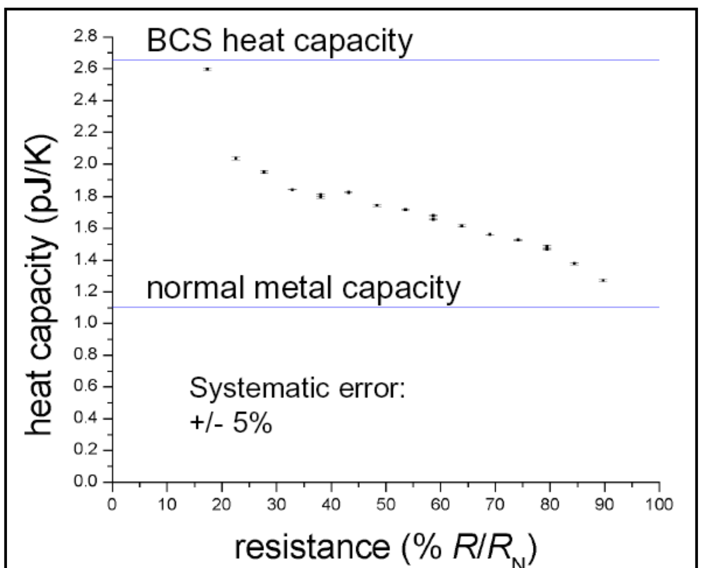
Continuing studies w.r.t. heat capacity, $R_{normal}$, $I_{critical}$; demonstrate reproducibility.

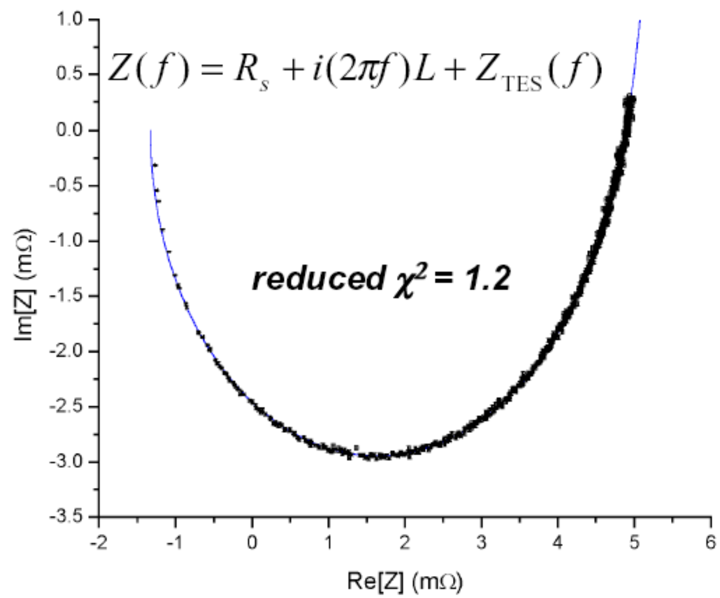
# Recent Progress and Issues (cont.)




## Impedance measurements yield device parameters:

| Measured parameters | Free parameters and statistical errors |
|---|---|
| $G$=344 pW/K | $\alpha$=172.3 +/- 0.7 |
| $I_0$=29.5 μA | $\beta$= 0.8518+/- 0.0008 |
| $R$=2.05 mΩ | $C$=(2.034 +/- 0.008) pJ/K |
| $R_S$=1.45 ohms | $L$=(262.9 +/- 0.6) nH |
| $T_0$=98.5 mK | |

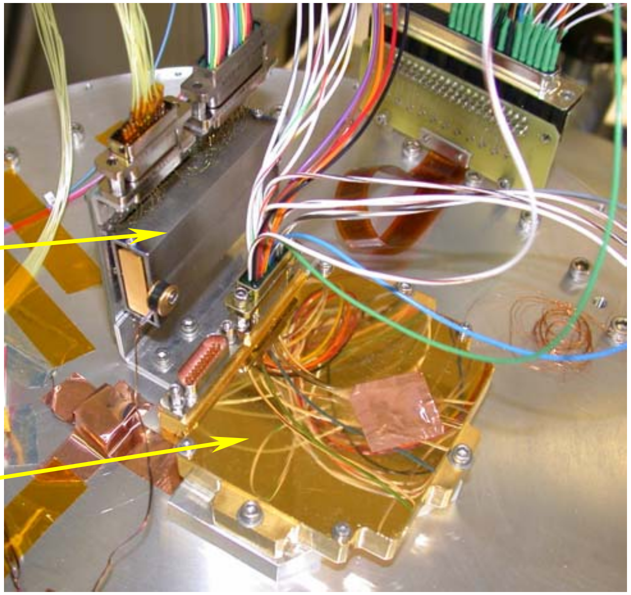


# Recent Progress and Issues (cont.)

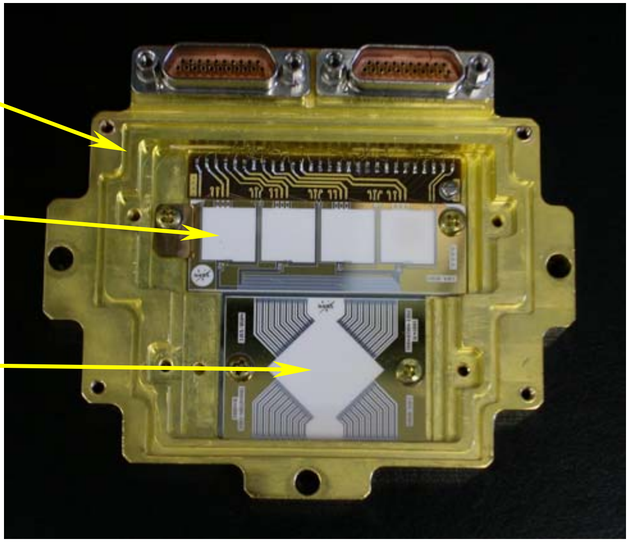
4-channel, 2-stage SQUID readout
Installed in dilution refrigerator

SQUID Array



Detector Box

1st stage SQUID board



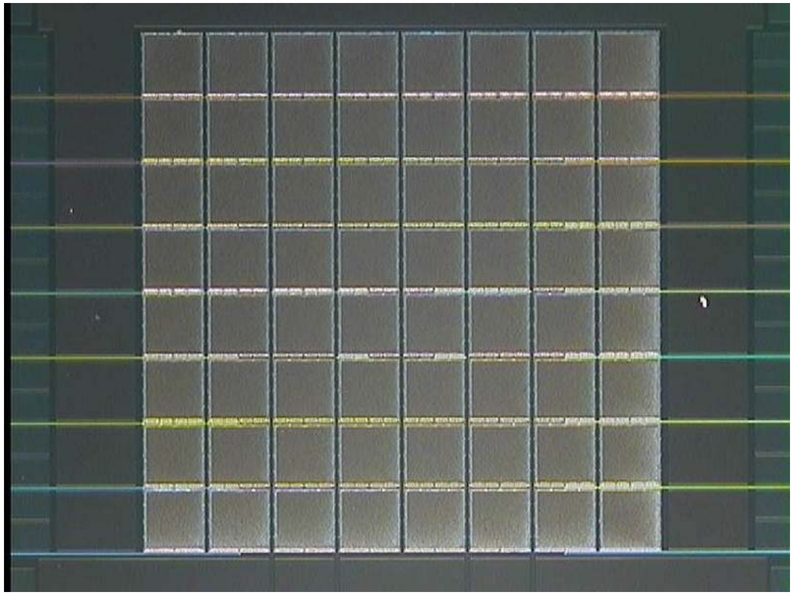
Detect board

# NIST:

Complete fabrication of 8x8 array of TES detectors using MEMS structures for the four-pixel demo.

Two of the inner 8-pixel columns and the inner four pixels are instrumented with electrical leads. Under-pixel wiring layers are not yet implemented. If it works, an array like this would be used in the NIST four-pixel demo.

Array chips were fabricated both with and without Bismuth absorbers. Single pixels from the arrays will be tested over the next month. A photograph of a completed 8x8 array:



# Recent Progress and Issues (cont.)

Tested new, dedicated superconducting bilayer deposition system. Fabricated films with target transition temperatures of close to 100 mK. Demonstrated run-to-run and across-wafer transition temperature variation of <~ 5 mK (1 $\sigma$).

Recently commissioned a second ADR for array testing. Now commissioning a third ADR for fast-cycling screening and measurements of transition temperature.

Progressing toward increasing bandwidth of TES MUX electronics from 3 MHz to 50 MHz.

# Recent Progress and Issues (cont.)

## NTD work at SAO:

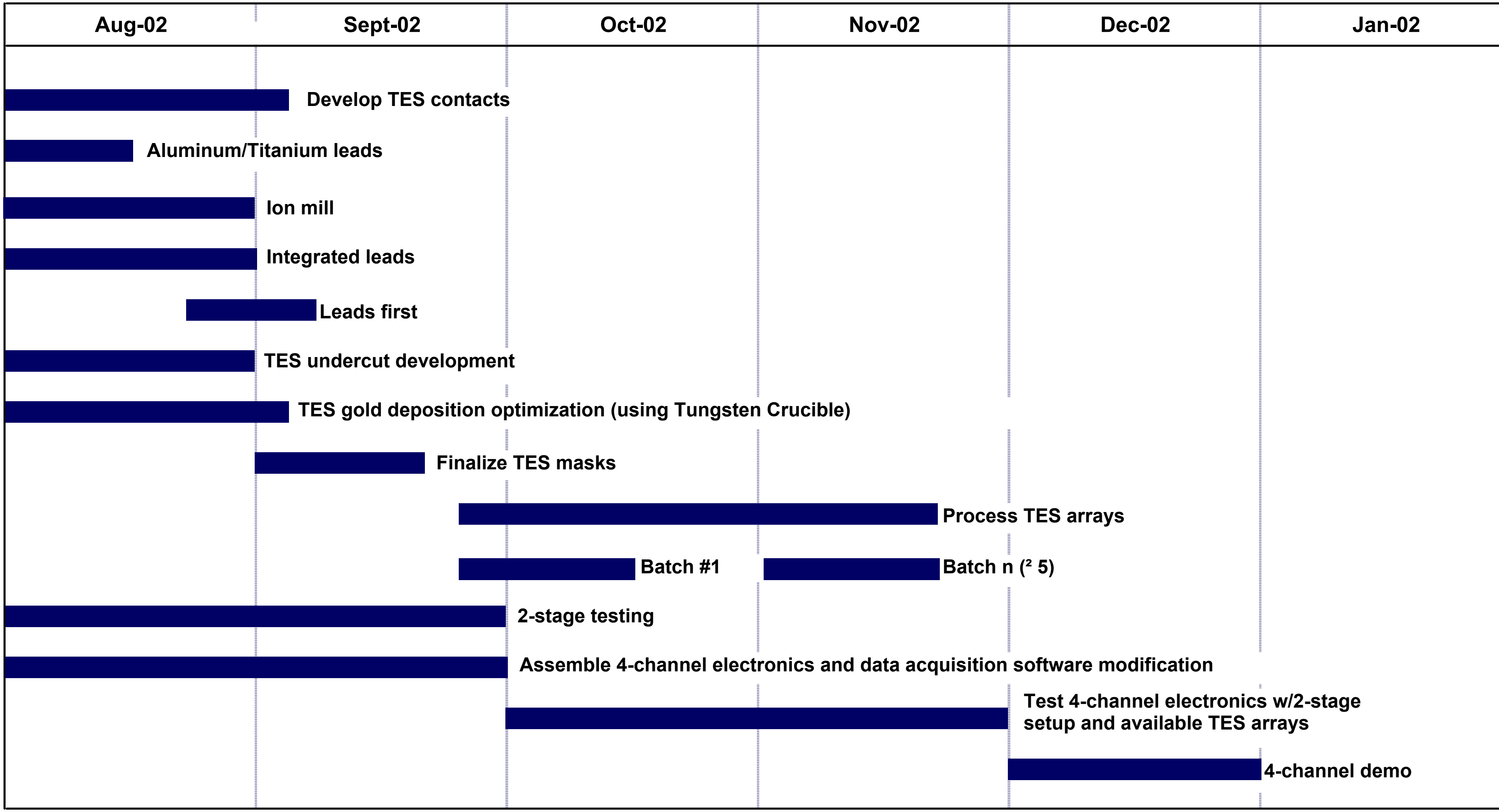
Four preamplifiers were fabricated and tested successfully

The 2-stage ADR for the 4 pixel demo is under construction

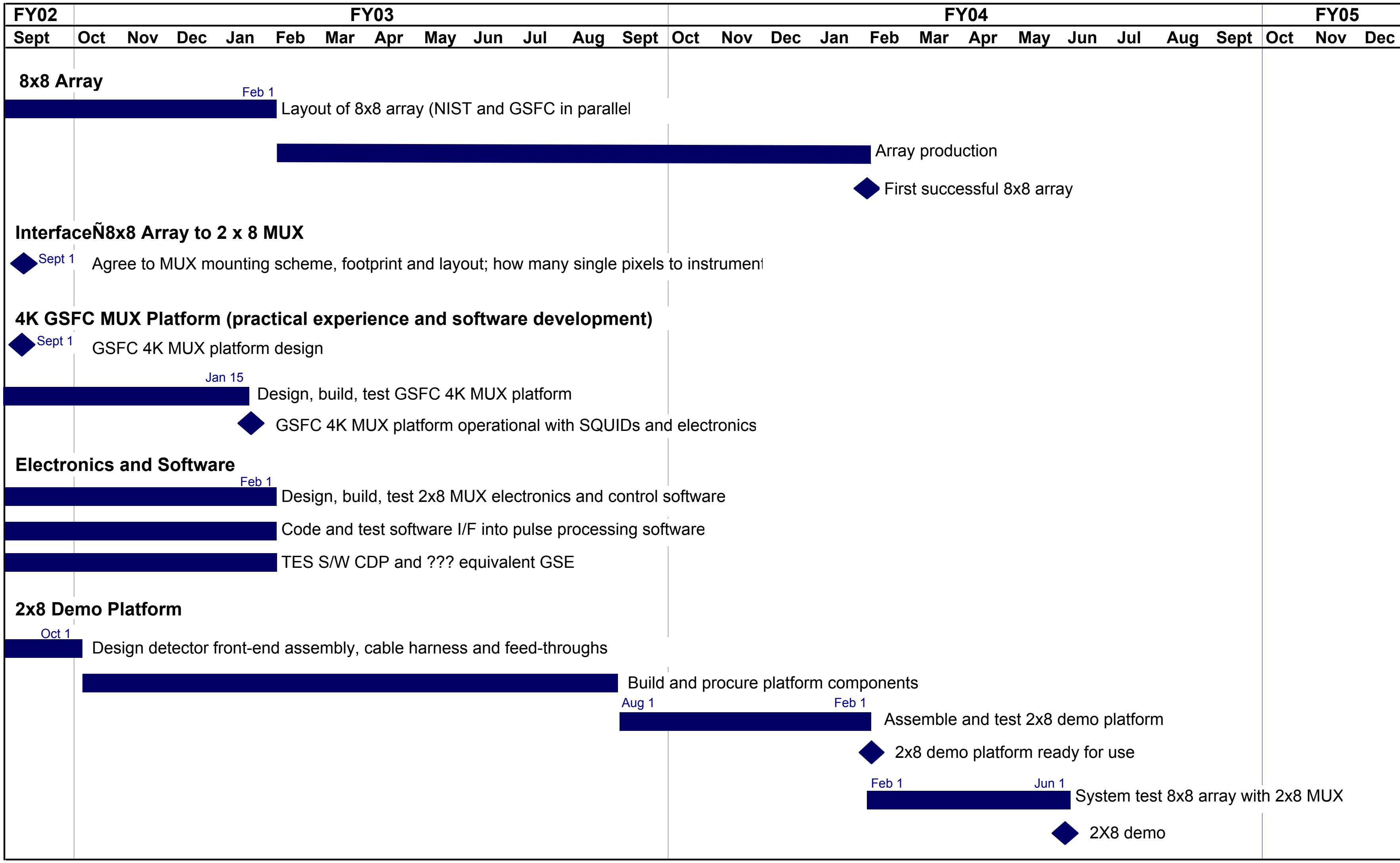
Have built some new devices with a thin layer of gold on the tin absorber to test the thermalization properties

We are investigating the effects of impurities in the tin absorber to improve the reproducibility of the temporal response of the detectors

# TES 2x2 Demo Schedule



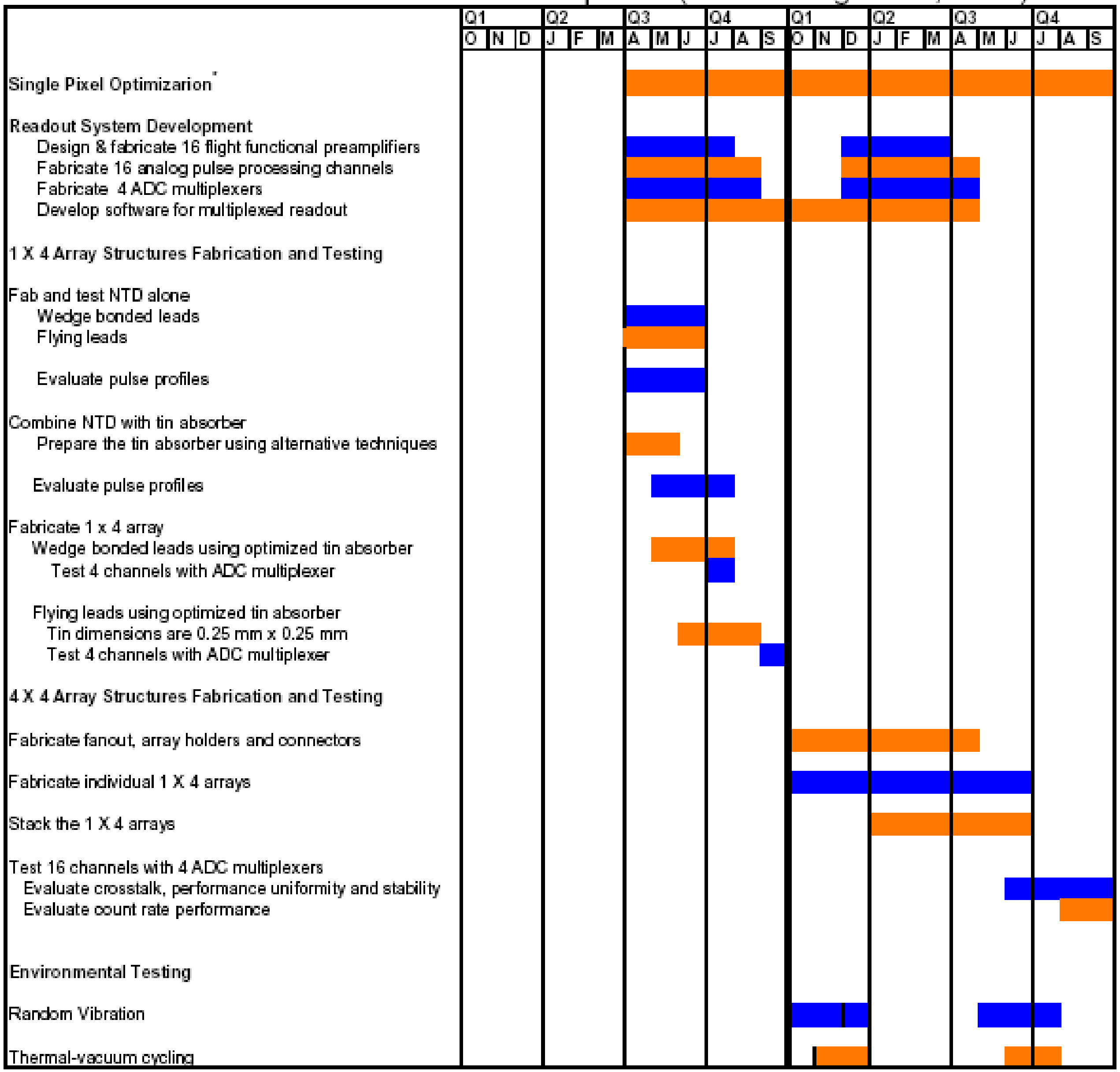
# Preliminary TES 2x8 Demo Schedule



# TES TRL-6 Costs ($K in FY02)

| Development Area | FY03 | FY04 | FY05 | |
|---|---|---|---|---|
| Thermal Conductance & Cross talk | 137 | 0 | 0 | 137 |
| Noise | 193 | 0 | 0 | 193 |
| Basic process, materials, and integration | 735 | 946 | 922 | 2,603 |
| Absorber Development | 103 | 0 | 0 | 103 |
| Electrical Cross Talk | 73 | 0 | 0 | 73 |
| Micro-vias and Interconnects | 139 | 235 | 237 | 611 |
| SQUID and MUX Chips | 350 | 350 | 350 | 1050 |
| MUX and Digital Processing Electronics | 414 | 435 | 363 | 1212 |
| Radiation Environment Studies | 74 | 160 | 249 | 483 |
| Thermal Staging/Detector Assembly | 178 | 215 | 155 | 548 |
| Wiring and B-field Shielding | 50 | 51 | 52 | 153 |
| 2 x 8 and 3 x 32 demonstrations | 143 | 429 | 243 | 815 |
| **Total required funding:** | **2,589** | **2,821** | **2,571** | 7,981 |
| **Total required from Con-X project:** | **2,019** | **2,521** | **2,571** | 7,111 |

# NTD Germanium Microcalorimeter Development (revised August 13, 2002)




* Single pixel optimization is being carried out using SR&T funds

# NTD Budget for FY2003

**Budget Summary for Research Proposal**

**Year 2**
**Total Period of Performance from October 1, 2002 to September 30, 2003**

| | A | NASA USE ONLY B | C |
|---|---|---|---|
| **1. Direct Labor (salaries, wages, and fringe benefits.)** | $136,476 | | |
| **2. Other Direct Costs:** | | | |
| a. Subcontracts | 289,120 | | |
| b. Consultants | 0 | | |
| c. Equipment | 49,920 | | |
| d. Supplies | 87,724 | | |
| e. Travel | 5,412 | | |
| f. Other | 37,037 | | |
| **3. Indirect Costs** | 71,800 | | |
| **4. Other Applicable Costs** | 0 | | |
| **5. Subtotal -- Estimated Costs** | 677,489 | | |
| **6. Less Proposed Cost Sharing (if any)** | | | |
| **7. Carryover Funds (if any)** | | | |
| a. Anticipated amount: | | | |
| b. Amount used to reduce budget | | | |
| **8. Total Estimated Costs** | $677,489 | | |

# TES Milestones, *continued*

## FY04

Design detector front-end assembly
Build up test platform for 3 x 32 demo

## FY05

Build and qualify 32 x 32 array

- individual pixel performance
- perform component vibration
- repeated thermal cycle evaluation

Perform 3 x 32 demo on 32 x 32 array
Demonstrate viable interconnect scheme for 32 x 32 array
Design particle rejection scheme
Design flight-worthy FEA

# TRL-6 Definition

## TRL 6 definition:

*system or sub-system prototype demonstration in relevant environment*

**System:**

Full-sized calorimeter array with cold and warm electronics. Full 32 x 32 read-out not necessary, but the extension from 3 x 32 to 32 x 32 must be possible through replication of existing hardware, and not further development.

**Relevant environment:**

Operation in an ADR (relevant magnetic environment), but not necessarily a Con-X flight ADR design.

Vibration and thermal cycle tests to be done at the component (calorimeter array) level.

# TES Milestones

## FY02

Determine baseline compact pixel design.

Study thermal cross talk and determine baseline array structure.

Incorporate “mushroom” absorbers with appropriate heat capacity onto compact pixels and evaluate thermalization performance.

Build up test platform for 2 x 8 demo.

Complete study of L2 radiation environment and impact on focal plane array and basic irradiation tests.

# TES Milestones, *continued*

## FY03

Determine baseline absorber design for TRL-6 demo

Determine baseline TES design for TRL-6 demo

Develop MUX and digital processor capable of reading out 2 x 8 demo

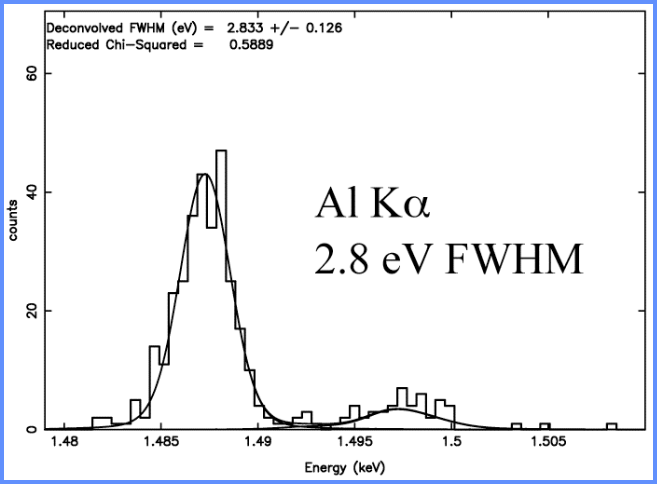
Complete electrical system model to understand susceptibilities to cross talk and pickup

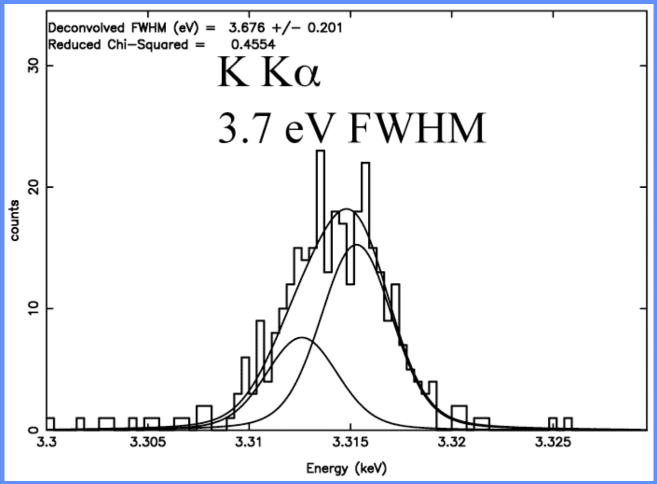
Build and qualify 8 x 8 array

- Individual pixel performance
- perform component vibration
- repeated thermal cycle evaluation

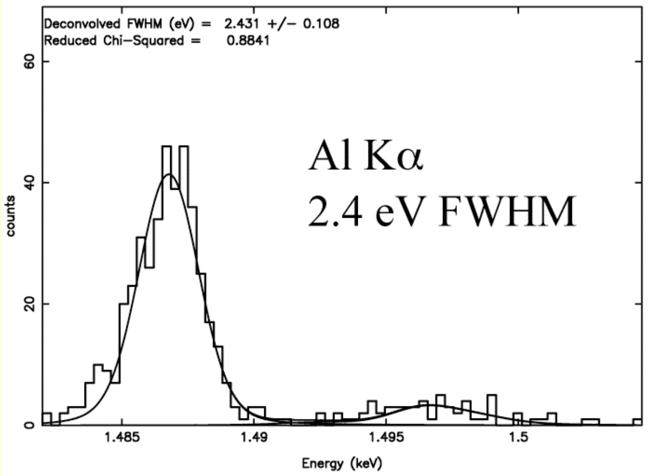
Perform 2 x 8 demo on 8 x 8 array

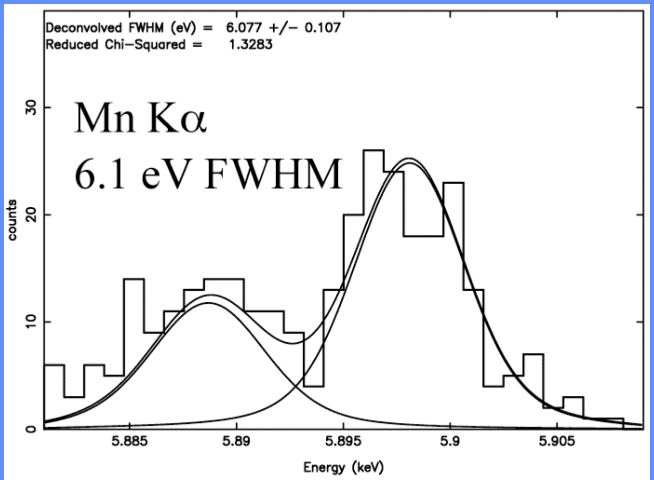
500 x 500 μm TES on 5 mm membrane



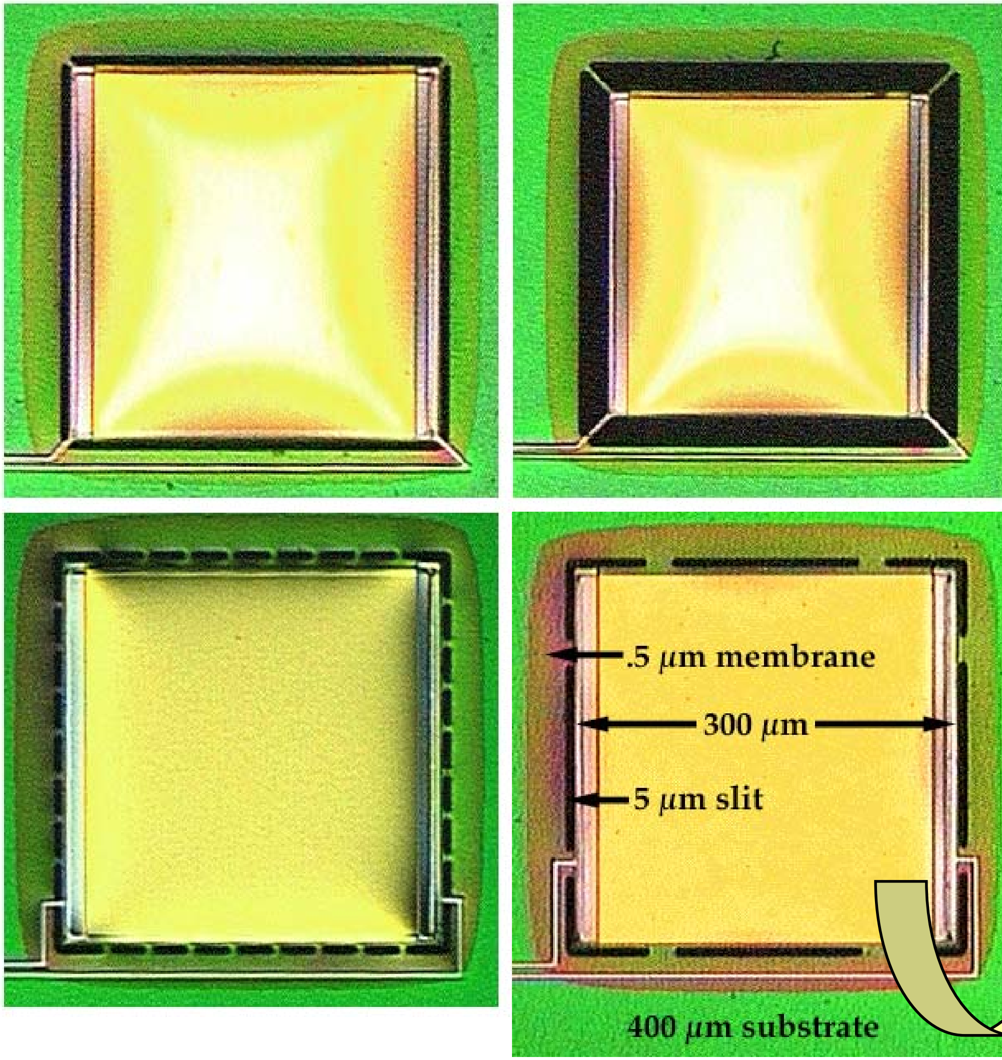

300 x 300 μm TES on 3 mm membrane



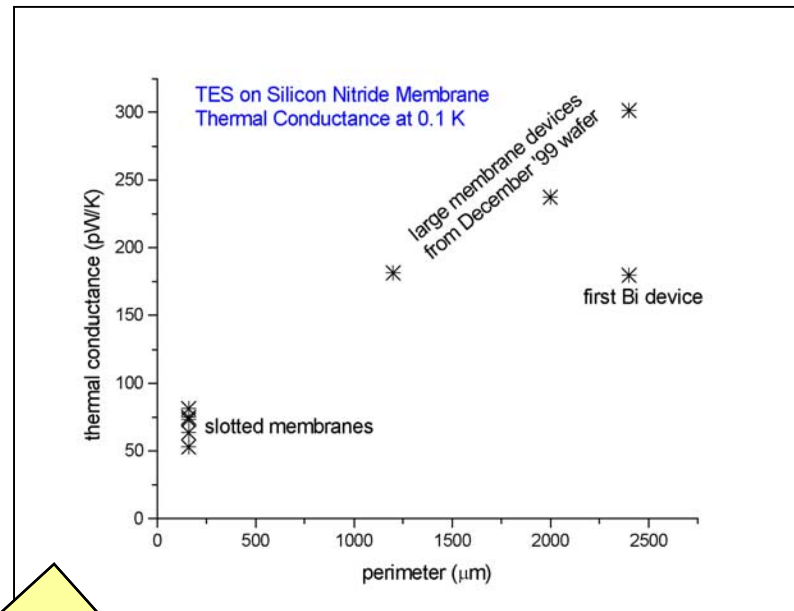




GSFC

# Testing Pixels with Con-X size




Individual TES devices designed to have different thermal conductance to allow parameterization.

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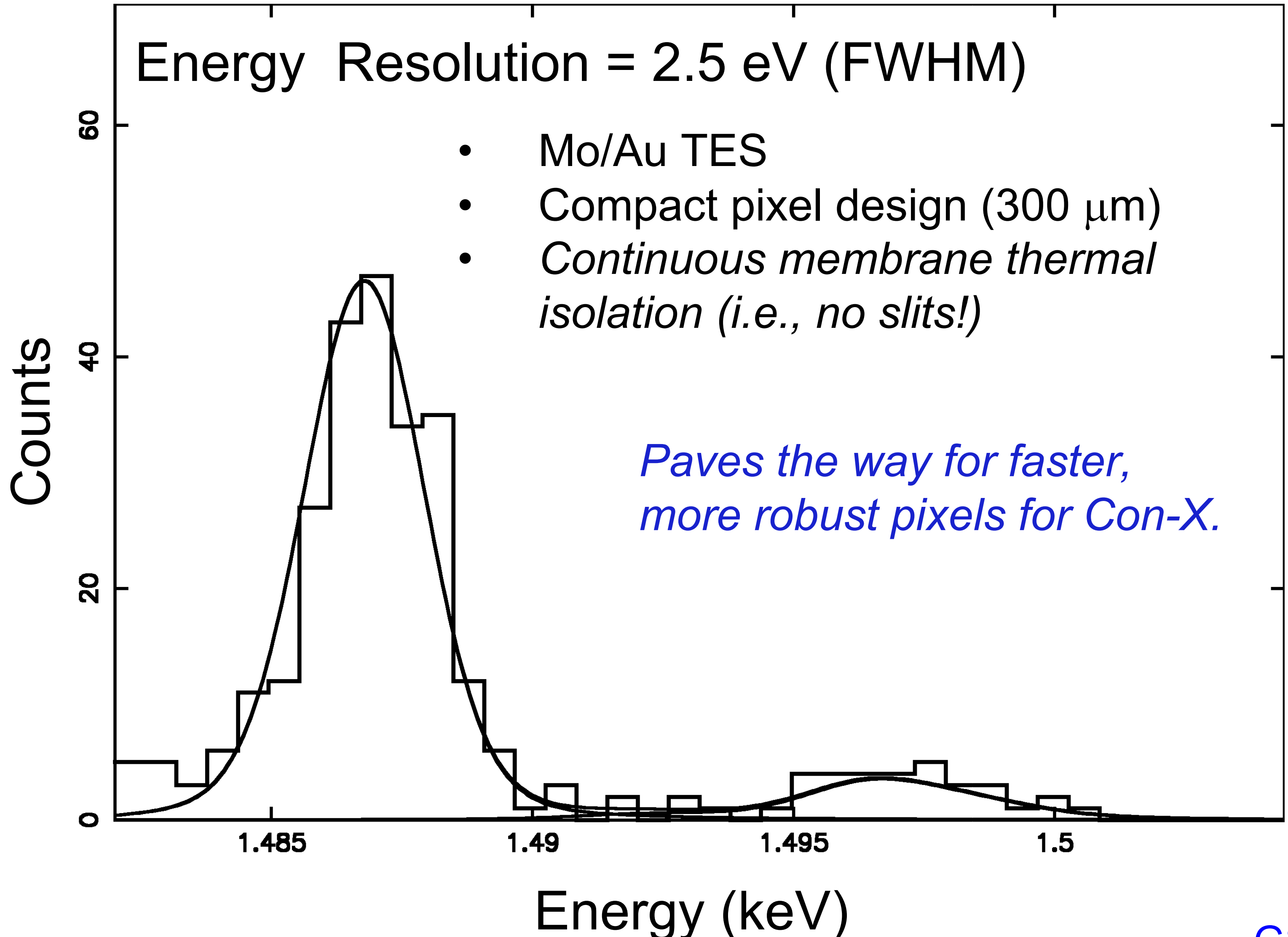
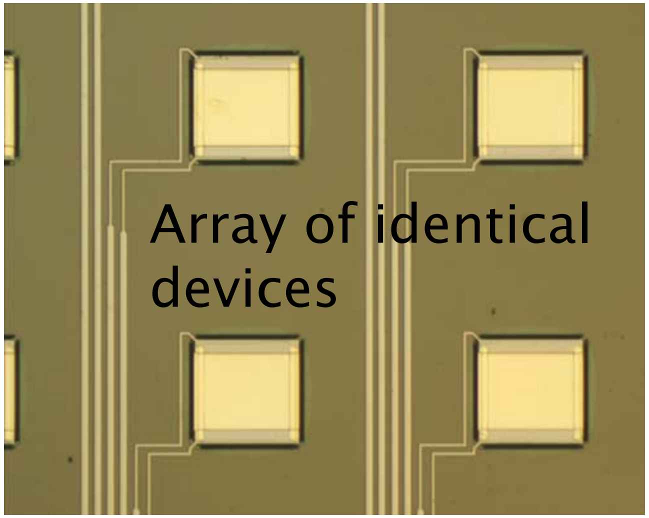
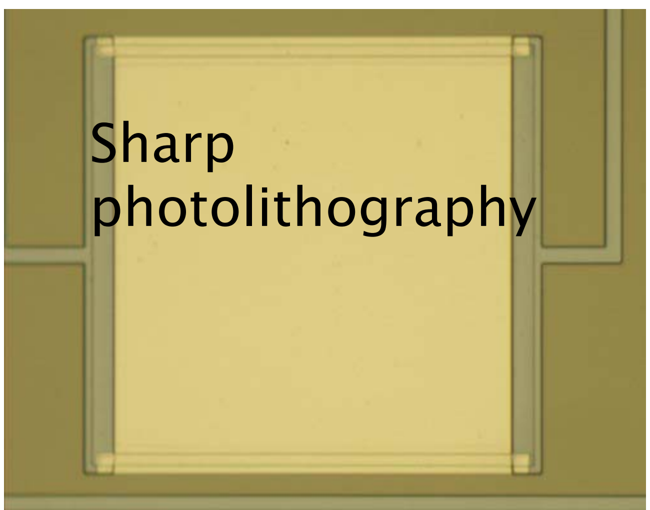
# Results from Compact TES Pixels

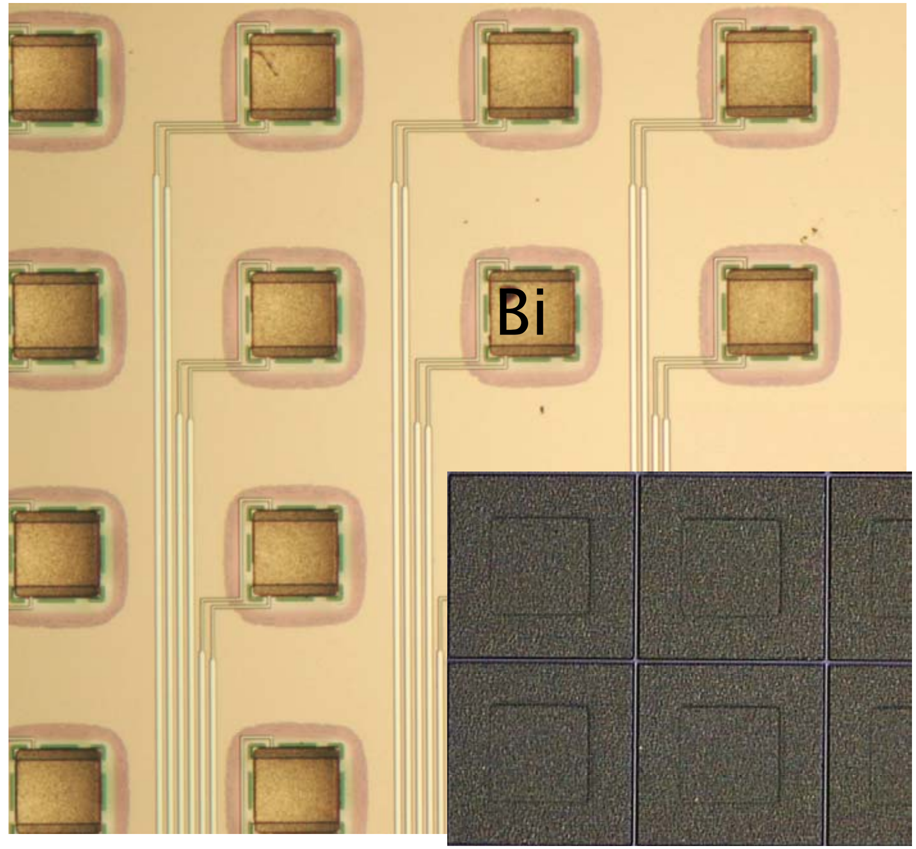



GSFC

# TES Fabrication Examples



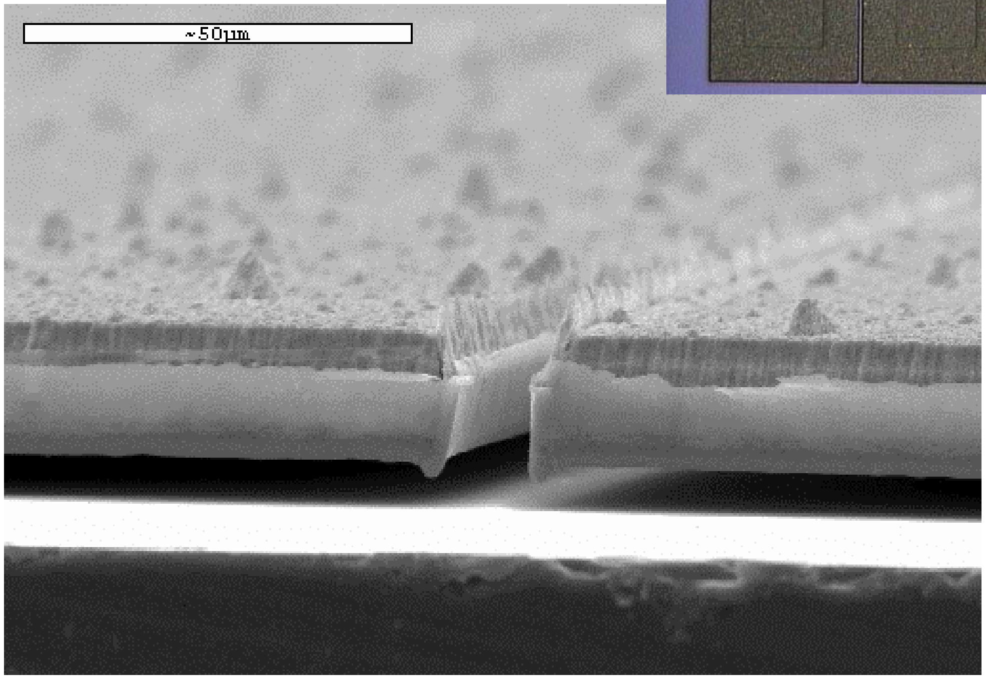



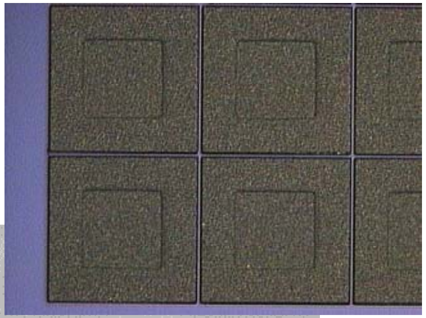

Array of identical 150 micron devices. Soon will make these with 250 and 400 micron "mushroom" absorbers. The Bi absorbers shown are the size of the stem in the mushroom.

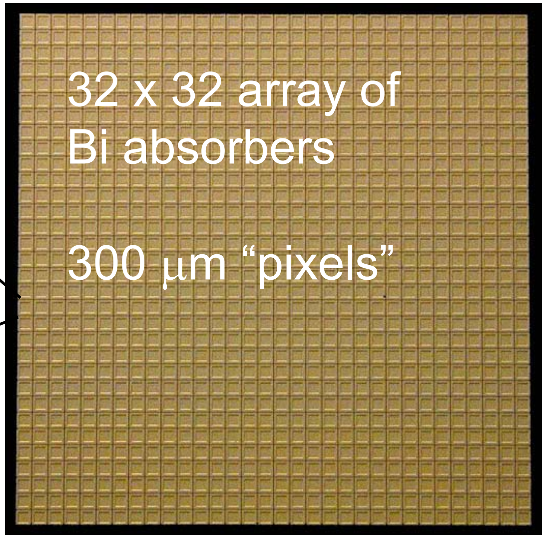
GSFC

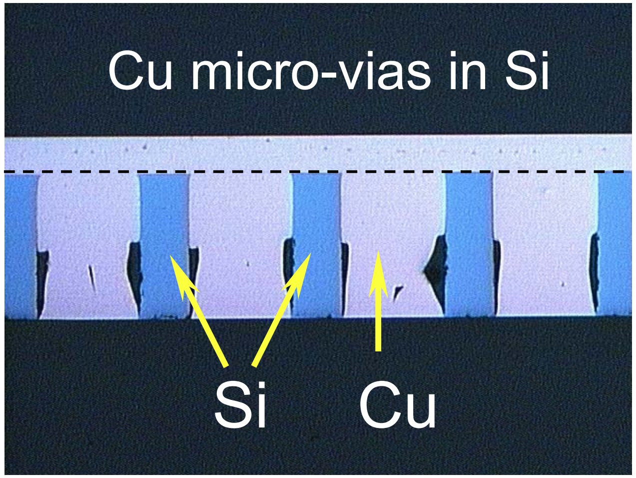
# Micromachined Bi Absorbers

Proof of concept for fabricating x-ray absorbers in array format with high filling factor.



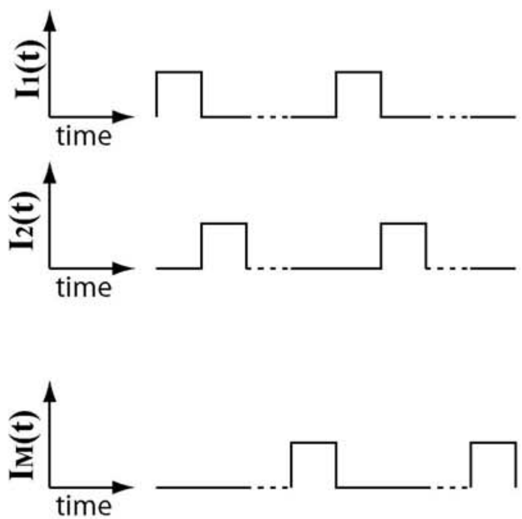



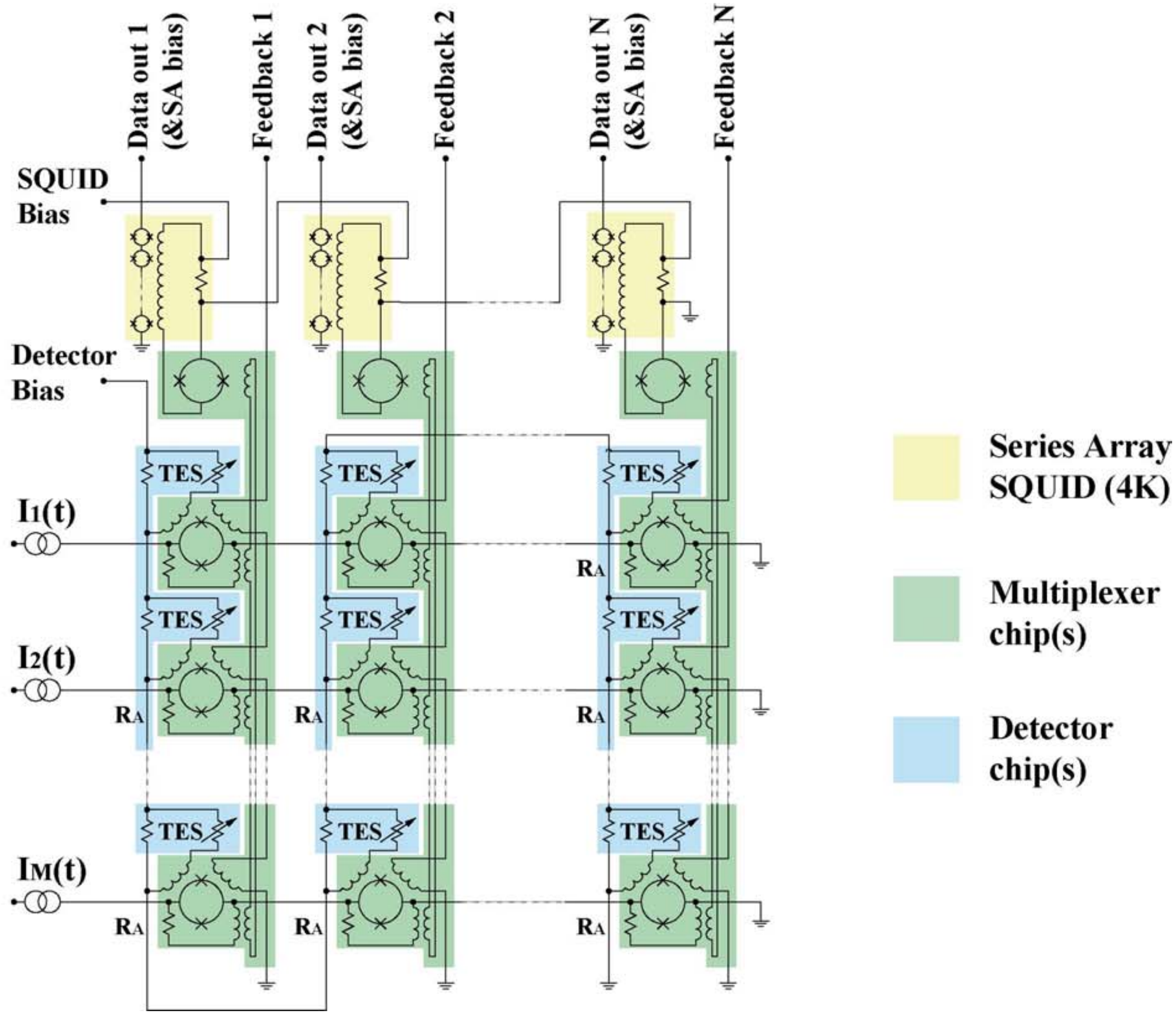


# SQUID Multiplexer Scheme

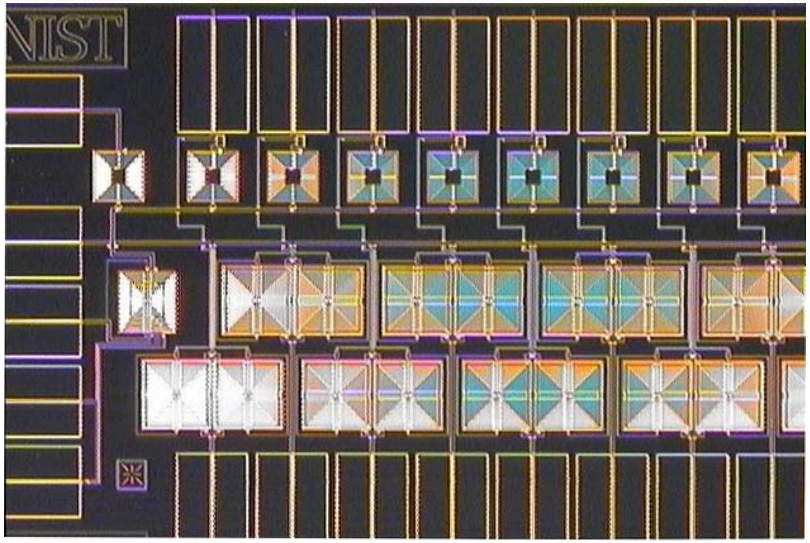
**Boxcar Modulation Functions**
(can be from Cryogenic CMOS MUX)



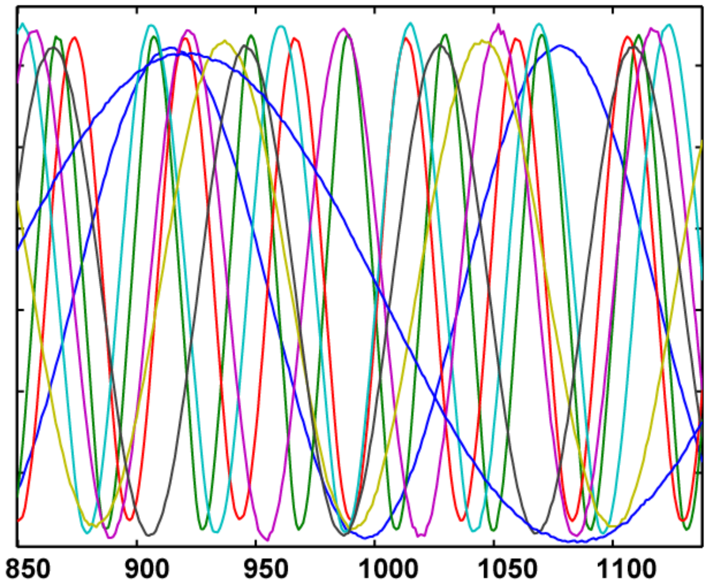




NIST/Boulder

# SQUID Multiplexer




- 32-channel MUX. (Need 32 chips to instrument kilopixel array.)
- First-generation MUX deployed in astronomical instrument (FIBRE) with GSFC
- Second generation improves crosstalk & power




- Switched digital feedback is working
- Can sample at 1.6 MHz line rate
- Sufficient performance for 2 × 8 demo array
- Need to increase bandwidth for full instrument

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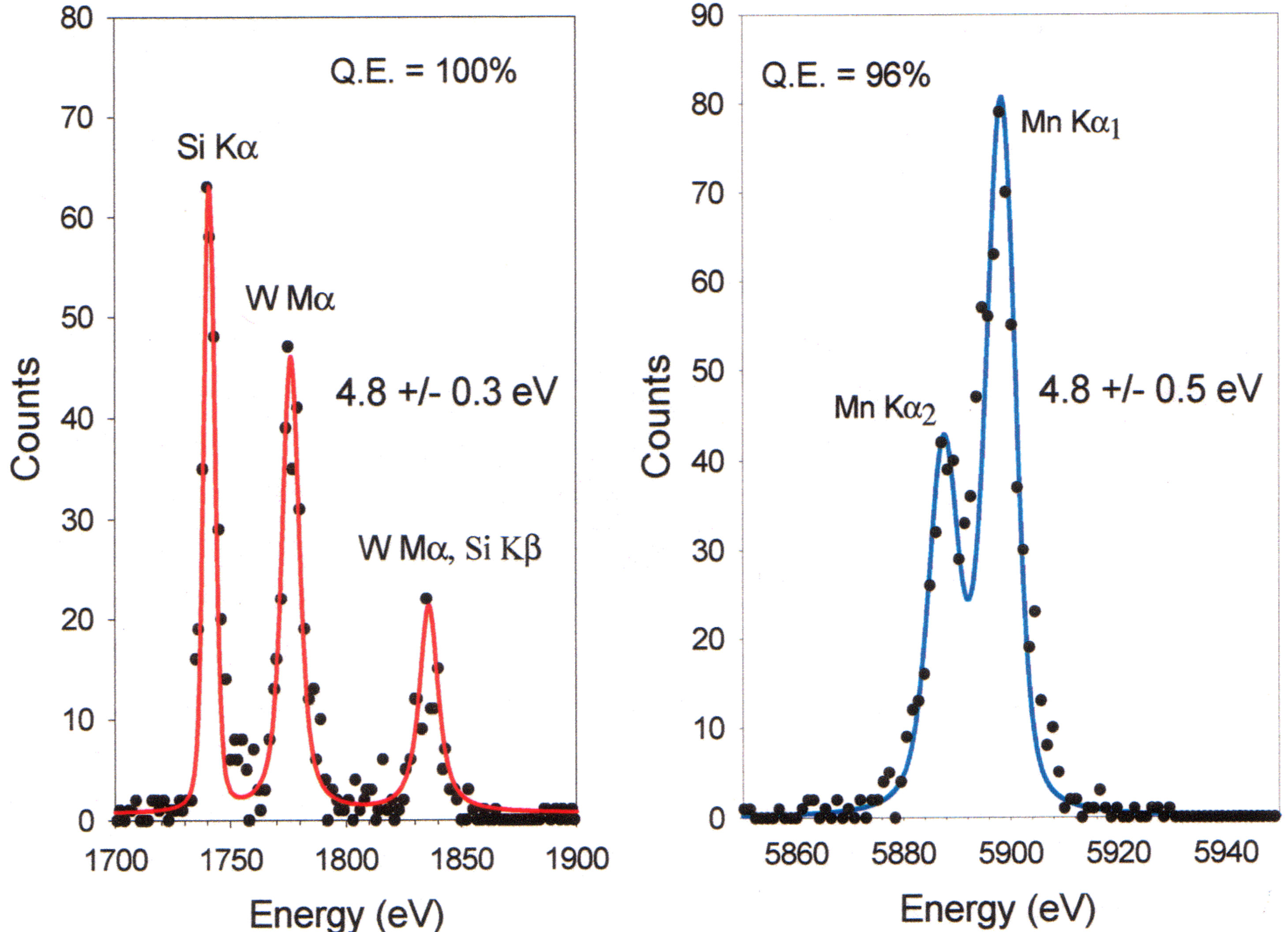
# NTD Calorimeter with Sn Absorbers




SAO